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Dynamics of force and muscle stimulation in human vertical jumping

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ABSTRACT

BOBBERT, M. F., and J. P. VAN ZANDWIJK. Dynamics of force and muscle stimulation in human vertical jumping. *Med. Sci. Sports Exerc.*, Vol. 31, No. 2, pp. 303–310, 1999. **Purpose:** The purpose of this study was to gain insight into the importance of stimulation dynamics for force development in human vertical jumping. **Methods:** Maximum height squat jumps were performed by 21 male subjects. As a measure of signal dynamics, rise time (RT) was used, i.e., the time taken by the signal to increase from 10% to 90% of its peak value. RT were calculated for time histories of smoothed rectified electromyograms (SREMG) of seven lower extremity muscles, net moments about hip, knee, and ankle joints, and components of the ground reaction force vector. **Results:** Average RT values were 105–143 ms for SREMG signals, 90–112 ms for joint moments, and 120 ms for the vertical component of the ground reaction force (F_z). A coefficient of linear correlation of 0.88 was found between RT of SREMG of m. gluteus maximus (GLU) and RT of F_z . To explain this correlation, it was speculated that for an effective transfer from joint extensions to vertical motion of the center of mass (CM), the motion of CM needs a forward component during the push-off. Given the starting position, only the hip extensor muscles are able to generate such a forward acceleration of CM. To preserve the forward motion of CM, RT of knee and ankle joint moments need to be adjusted to RT of the hip joint moment. Thus, the greater RT of the hip joint moment and RT of GLU-SREMG, the greater RT of F_z . **Conclusions:** Overall, it was concluded that the time it takes to develop muscle stimulation has a substantial effect on the dynamics of force development in vertical jumping, and that this effect should not be neglected in studies of the control of explosive movements. **Key Words:** RISE TIME, EMG, JOINT MOMENTS, GROUND REACTION FORCES, CONTROL

In explosive movements, achieving a high velocity of some part of the body is a prerequisite for successful performance. An example of an explosive movement is throwing, where the velocity of the hand, and consequently that of the projectile, is an important factor determining throwing distance. Another example is vertical jumping, where the vertical velocity of the trunk is of decisive importance for jump height. In a single-joint motion, started at zero velocity from a given initial angle, the velocity achieved after a given angular displacement depends on the amount of net work produced by the muscles crossing that joint. Because net work equals the integral of net joint moment with respect to joint angle, maximum performance is achieved if net moment is maximal over the complete range of motion. Unfortunately, it takes time for muscle force, and therewith joint moment, to attain its maximum. Thus, net work is limited by the time required for force development: the greater this time, the greater the angular displacement traveled at submaximal moment, and the greater the work deficit. It has been shown that the time required for force development in human subjects is an important factor determining mechanical output in single-

joint movements (5,6,9), as well as in complex multijoint activities such as vertical jumping in which the transformation of work produced into effective energy is an additional problem (4). Because of its effect on work output, the time required for force development has even been indicated as the problem to the solution of the countermovement. The idea here is that the countermovement solves this problem by allowing subjects to build up force before shortening begins (1,4,10,17,19,21,29).

Generally speaking, force development is the outcome of a number of dynamic processes in series, including stimulation dynamics, excitation dynamics, and contraction dynamics (38). In this article, stimulation dynamics refers to the temporal aspects of building up the stimulation input to the muscles, excitation dynamics refers to the process of developing active state in response to an increase in stimulation, and contraction dynamics refers to that of developing force in response to an increase in active state. Of these different processes, contraction dynamics, which involves the interaction between the contractile machinery and series elastic structures, is most easily studied. Many investigations have been aimed at determining force-velocity relationships of human muscles (e.g., 12,15,18,23,24,31,34,35,39) and compliance of series elastic structures (e.g., 14,15,39). Excitation dynamics in human muscle has also received attention. Initially, estimation of the temporal aspects of excitation development was hampered by the uncertainty still surrounding the contraction dynamics of human muscle (13,26). Recently, however, Zandwijk et al. (39)

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estimated for the plantar flexors of four subjects both the parameters describing contraction dynamics and those describing excitation dynamics. Stimulation dynamics in voluntary contractions has received no explicit attention. In models developed for simulation of explosive movements, muscle stimulation is typically increased to its maximum instantaneously (e.g., 20,22,28,37). From control theory it follows that this so-called “bang-bang” control produces a maximum performance (22). In human subjects, however, instantaneous changes in muscle stimulation will be precluded by the dynamics of motoneuron pool excitation (8) and perhaps also by the central commands themselves.

Because stimulation dynamics, excitation dynamics, and contraction dynamics are in series, the slowest of these processes will have a dominant effect on the temporal aspects of force development. It has been suggested that in human vertical jumping, the time required for development of muscle stimulation is not negligible (4), and the purpose of the present study is to gain more insight into the importance of stimulation dynamics for force development in human maximum height jumping. For this purpose, we first quantitated rise time (RT) of forces and electromyograms (EMG) measured during maximum height squat jumps of human subjects (EMG activity was assumed to reflect muscle stimulation, even though it is technically speaking an output signal of the muscle rather than the input signal). If stimulation is indeed developed relatively slowly, differences in stimulation dynamics among subjects could manifest themselves in differences in force dynamics. Therefore, we investigated to what extent the variation across subjects in the RT of force during jumping was explained by variation in RT of electromyographic activity.

METHODS

Subjects and experimental protocol. A group of 21 male subjects, all actively engaged in various sports, participated in this study. Informed consent was obtained from all subjects in accordance with the policy statement of the American College of Sports Medicine. Characteristics of the group of subjects (mean \pm SD) were: age, 25 ± 4 yr; height, 1.88 ± 0.10 m; and body mass 79.8 ± 7.5 kg. Retroreflective spheres corresponding to anatomical landmarks were fixed to each subject, and pairs of surface electrodes were applied to the skin overlying m. semitendinosus (ST), m. biceps femoris caput longum (BF), m. gluteus maximus (GLU), m. rectus femoris (RF), m. vastus lateralis (VL), m. gastrocnemius (GAS), and m. soleus (SOL). After warming up, each subject performed, with arms akimbo, maximum height squat jumps, i.e., maximum vertical jumps in which the subjects were instructed to start from a semi-squatted position and to initiate the push-off without making a preparatory countermovement.

During jumping, the positions of the retroreflective spheres were monitored using electronically shuttered cameras (NAC 60/200 MOSTV) connected to a VICON high-speed video analysis system (Oxford Metrics Ltd., Oxford, U.K.). Ground reaction forces were measured using a force

plate (KISTLER type 9281B, Kistler Instrumente AG, Winterthur, Switzerland) connected to an electronic amplifier unit (KISTLER type 9281B, Kistler Instrumente AG). Electromyograms were preamplified and transmitted using a telemetry system (BIOMES 80, Glonner Electronics GmbH, Munich, Germany), further amplified, high-pass filtered at 7 Hz to reduce the amplitude of possible movement artifacts, full-wave rectified, smoothed using an analog 20-Hz, third-order, low-pass filter, and sampled at 200 Hz simultaneously with the kinematic data and ground reaction forces. Off-line, the preprocessed EMG signals were further smoothed using a bidirectional digital low-pass Butterworth filter with a 10-Hz cutoff frequency. The resulting signals will henceforth be referred to as SREMG (smoothed rectified EMG). Sagittal plane coordinates of the anatomical landmarks were reconstructed from individual camera views using AMASS software (Oxford Metrics Ltd., Oxford, U.K.) and used to calculate jump height, defined as the difference between the height of the center of mass of the body (CM) at the apex of the jump and the height of CM when the subject was standing upright with heels on the ground. Furthermore, landmark coordinates were combined with ground reaction forces to calculate net moments at hip, knee, and ankle joints (M_H , M_K , and M_A , respectively). Further details on the collection of data and the kinematic, kinetic, and electromyographic analyses can be found elsewhere (4).

For the purpose of this study, it was required to conveniently quantitate the dynamics of stimulation and force development. The choice was pitched upon RT. In electronics, RT is a concept used in the studying the response of a low-pass network to a pulse input and is defined as the time taken by the signal to increase from 10% to 90% of its maximal value (27). This definition, however, required modification for the signals of interest in this study, i.e., time histories of SREMG, net joint moments, and vertical and horizontal components of ground reaction force (F_z and F_y , respectively). In this study, RT was defined as the time taken by the signal to increase from $S+0.1(P-S)$ to $S+0.9(P-S)$, where P is a peak value of the signal and S is a starting value. For time histories of mechanical variables, we used for P the maximal value attained during the push-off and for S the minimal value attained before the instant that P is reached. The determination of RT for M_K and F_z is illustrated in the two lowermost panels in Figure 1. For time histories of SREMG, we used for S the average SREMG level in the starting position and for P the maximal value of the first major burst. This first major burst was identified using the following steps: 1) find the maximal value M of the signal in the time period up to 150 ms before toe-off, and 2) find the instant t_1 that the signal rises above 0.7 M , 3) search from t_1 forward in time for the instant t_2 that the signals decreases below 0.7 M (note that t_2 may occur later than 150 ms before toe-off). The peak value of the signal between t_1 and t_2 was subsequently substituted for P . Examples of the results applying the method to SREMG signals are presented in the four topmost panels of Figure 1. It needs no argument that the laborious detour of identifying

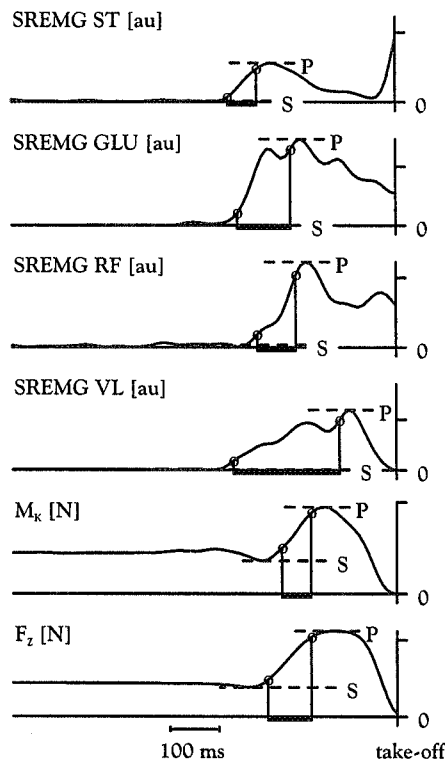


Figure 1—Illustration of quantitation of signal dynamics. Signals shown are time histories of the vertical component of the ground reaction force (F_z), net knee joint moment (M_k), and, in arbitrary units (au), smoothed rectified electromyograms (SREMG) of m. vastus lateralis (VL), m. rectus femoris (RF), m. gluteus maximus (GLU), and m. semitendinosus (ST). For each signal, two values were determined, a starting value (S) and a peak value (P). For precise definition of S and P, see text. Rise time (horizontal bars below abscissae) was defined as the time taken by the signal to increase from $S+0.1(P-S)$ (left circles) to $S+0.9(P-S)$ (right circles).

the “first major burst” was introduced to accommodate a minority of tricky SREMG signals, such as the one presented in the topmost diagram in Figure 1. In the remainder of this paper, $t_{0.1E}$ will refer to the instant that a signal reaches $S+0.1(P-S)$ and $t_{0.9E}$ to the instant that it reaches $S+0.9(P-S)$. Hence, $RT = t_{0.9E} - t_{0.1E}$.

Statistical analysis. In addition to calculating means and standard deviations, it was investigated whether sequence effects occurred in $t_{0.1E}$ and $t_{0.9E}$ of different variables. This was done by ordering the values within each subject and carrying out an ANOVA for ranked data (36) using the χ^2 statistic for hypothesis testing. If a statistically significant χ^2 value was found ($P < 0.05$), differences in $t_{0.1E}$ and $t_{0.9E}$ between selected variables were tested to significance using a sign test. To avoid the so-called electromechanical delay (e.g., 32) from causing false detection of differences, values for $t_{0.1E}$ and $t_{0.9E}$ of SREMG were not mixed with those of mechanical variables. Finally, to examine the interdependency of variables, coefficients of linear correlation were calculated for combinations of push-off time, jump height, and RT of SREMG signals, joint moments, and the components of the ground reaction force vector F_z and F_y .

SUBJECT PERFORMING MAXIMUM HEIGHT SQUAT JUMP

vertical velocity of CM at take-off: 2.86 m/s

jump height: 0.53 m

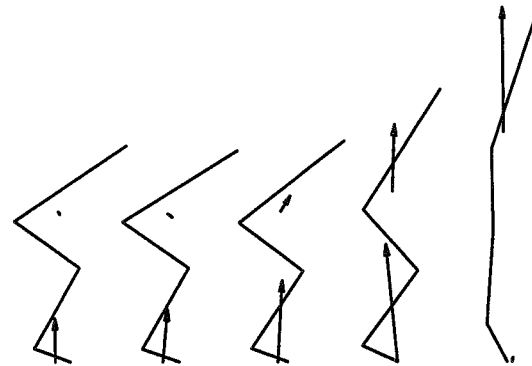


Figure 2—Stick diagrams of body configurations for one subject performing a vertical squat jump. The leftmost stick diagram depicts the initial configuration, the rightmost one the configuration at the last frame before toe-off. Diagrams are spaced 110 ms in time. In each one, the ground reaction force vector is represented with its origin at the center of pressure on the force platform, and the velocity vector of the mass center of the body is shown with its origin in the location of this mass center.

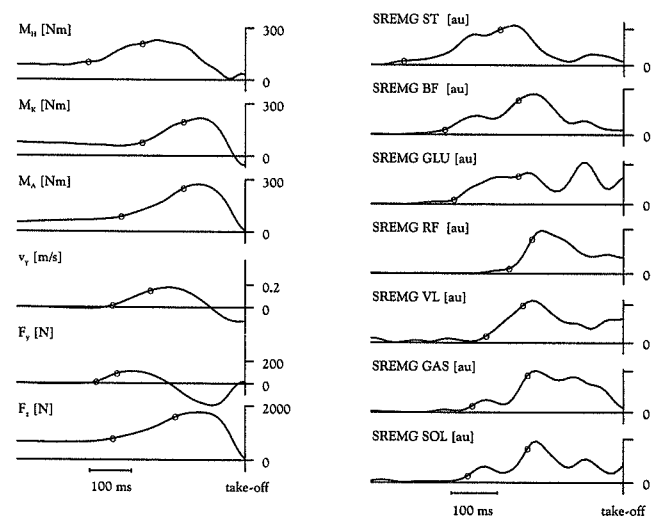


Figure 3—Time histories of several variables for one subject (same as in Fig. 2) performing a vertical squat jump. Variables are vertical and horizontal components of the ground reaction force (F_z and F_y , respectively), horizontal velocity of the center of mass (v_{cm}), net moments about ankle, knee, and hip (M_A , M_K , and M_H , respectively), and smoothed rectified electromyograms (SREMG) (in arbitrary units) of m. soleus (SOL), m. gastrocnemius (GAS), m. vastus lateralis (VL), m. rectus femoris (RF), m. gluteus maximus (GLU), m. biceps femoris (BF), and m. semitendinosus (ST). The time interval between each pair of circles is the rise time of the signal (cf., Fig. 1).

RESULTS

Figure 2 presents stick figures for a subject performing a maximum height squat jump, and Figure 3 presents for the same subject a typical series of time histories of F_z , F_y , joint moments and SREMG of the seven muscles, with $t_{0.1E}$ and $t_{0.9E}$ indicated. Table 1 presents mean values and standard deviations for $t_{0.1E}$, $t_{0.9E}$ and RT. Jump height amounted to 44 ± 5 cm and push-off time, defined as the time from $t_{0.1E}$

TABLE 1. Mean values \pm SD for the group of subjects ($N = 21$) of time instants at which the amplitude of different variables attained 10% and 90% of excursion ($t_{0.1E}$ and $t_{0.9E}$ respectively) as well as rise time (RT).

	$t_{0.1E}$ (ms)	$t_{0.9E}$ (ms)	RT (ms)
SREMG ST	-85 ± 49	47 ± 67	131 ± 65
SREMG BF	-81 ± 51	51 ± 91	133 ± 76
SREMG GLU	-41 ± 42	65 ± 64	106 ± 50
SREMG RF	1 ± 48	138 ± 74	137 ± 68
SREMG VL	-54 ± 43	86 ± 87	140 ± 90
SREMG GAS	4 ± 102	109 ± 102	105 ± 78
SREMG SOL	-30 ± 89	113 ± 106	143 ± 91
M_{Hh}	-23 ± 26	66 ± 33	90 ± 27
M_K	17 ± 37	126 ± 49	109 ± 44
M_A	22 ± 42	134 ± 51	112 ± 40
v_y	-70 ± 133	104 ± 59	174 ± 96
F_y	-75 ± 83	42 ± 51	117 ± 55
F_z	0 ± 0	120 ± 47	120 ± 47

For definition of $t_{0.1E}$, $t_{0.9E}$ and RT, see Figure 1. Time instants are expressed in ms relative to the instant that F_z reached $t_{0.1E}$. Variables are time-histories of the vertical and horizontal components of the ground reaction force (F_z and F_y , respectively), horizontal component of the velocity of the center of mass (v_y), net moments about ankle, knee and hip (M_A , M_K and M_{Hh} , respectively), and smoothed rectified electromyograms (SREMG) of m. soleus (SO), m. gastrocnemius (GAS), m. vastus lateralis (VL), m. rectus femoris (RF), m. gluteus maximus (GLU), m. biceps femoris (BF) and m. semitendinosus (ST).

of F_z to toe-off, was 329 ± 73 ms. Rank tests revealed statistically significant sequence effects among $t_{0.1E}$ of SREMG of the muscles and $t_{0.1E}$ of M_{Hh} , M_K , M_A , and F_z . The same was true for $t_{0.9E}$. The results of testing specific hypothesis will be presented in the discussion when appropriate.

Let us now highlight a few aspects of the horizontal motion of CM (center of mass of the body), which will play an important role in the discussion. In the starting position, CM was located on average 3.0 ± 4.3 cm frontal of the lateral malleoli of the ankles. During the first part of the push-off, it was accelerated in a forward-upward direction, as can be concluded from the changes in the ground reaction force vector (Fig. 2). F_y first displayed a positive (forward) thrust. It started to increase some 75 ms before $t_{0.1E}$ of F_z and reached a maximum value of 128 ± 78 N some 50 ms after $t_{0.1E}$ of F_z . After reaching its peak, F_y quickly decreased to reach a negative peak of -196 ± 92 N some 80 ms before toe-off. As a result of these horizontal accelerations, the horizontal component of the velocity of CM first increased to a maximum of 0.18 ± 0.11 m·s⁻¹ at some 120 ms after $t_{0.1E}$ of F_z , and thereafter decreased to -0.05 ± 0.09 m·s⁻¹ at toe-off. To convince the reader that the global motion of CM was a systematic one, CM trajectories of all subjects are displayed in Figure 4. Only in one of the 21 subjects was the net displacement of CM during the push-off negative (backward).

It may be concluded from the results presented in Table 1 that considerable variation occurred among the subjects in RT values, with coefficients of variation ranging from 30% (M_{Hh}) and 39% (F_z) to 75% (GAS-SREMG). To illustrate the variability in RT of F_z , Figure 5 presents time histories of F_z recorded in three different subjects labeled S1, S2, and S3. The jump heights of these subjects were 50 cm, 42 cm, and 35 cm, respectively. To identify the source of variation in RT of F_z and RT of other variables, correlation analysis was carried out. Table 2 presents statistically significant results

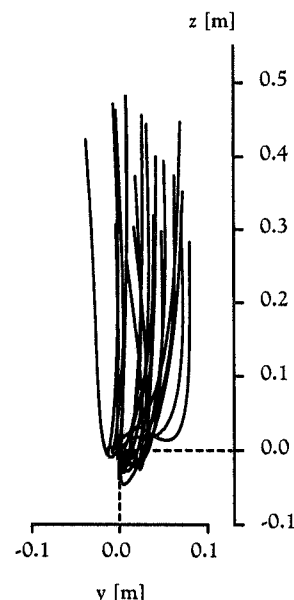


Figure 4—Individual trajectories of the center of mass (CM) during the squat jump push-off for all subjects participating in this study. Displacements are shown relative to the position of CM in the starting position, indicated by the dashed lines.

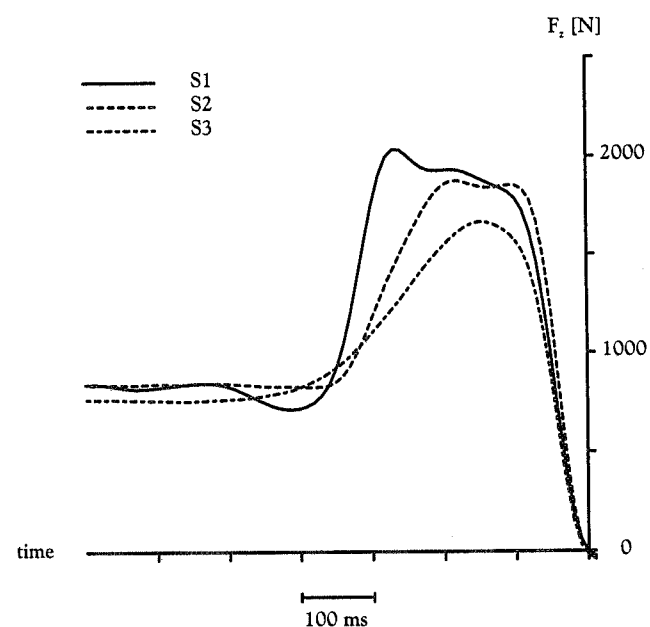


Figure 5—Individual time histories of the vertical component of the ground reaction force (F_z) for three subjects (S1, S2, and S3). Note the differences in rise time of F_z .

($P < 0.05$) of the correlation analysis on RT values, push-off time, and jump height. Correlations of around 0.7 or above (i.e., some 50% or more of variance explained) were found between RT of F_z and RT values of the joint moments and GLU-SREMG. It was concluded from scatter plots, such as the one presented in Figure 6b (RT of GLU-SREMG versus RT of F_z), that the high correlations were no artifacts due to uneven distribution of data points.

It was expected that statistically significant correlations would occur between RT of joint moments and SREMG of the muscles contributing to these moments. We did find

TABLE 2. Correlation coefficients for combinations of rise times of signals.

M_H	0.63	—	0.70	—	—	—	—	—	—	—
M_K	—	—	0.60	—	—	—	—	0.40	—	—
M_A	0.70	—	0.76	—	0.40	—	—	0.79	—	—
F_z	0.47	—	0.88	—	0.38	—	—	0.78	0.67	0.76
	SREMG ST	SREMG BF	SREMG GLU	SREMG RF	SREMG VL	SREMG GAS	SREM G SOL	M_H	M_K	M_A

Only statistically significant correlations ($P < 0.05$) are shown. Meaning of abbreviations as in Table 1.

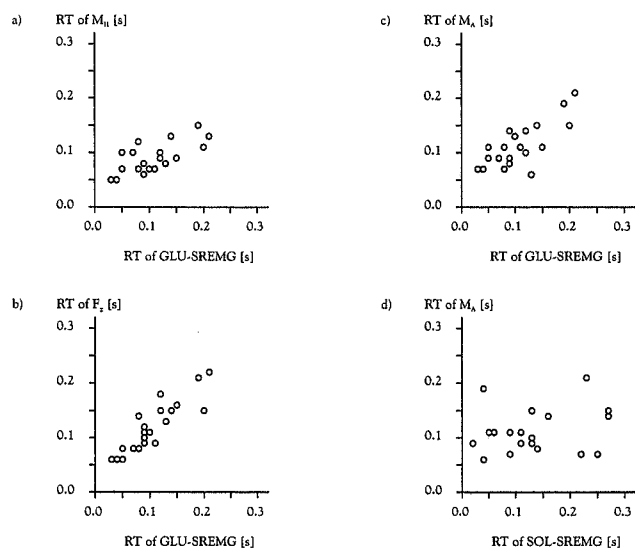


Figure 6—Scatter diagrams for combinations of rise times (RT) found in the group of subjects ($N = 21$, but some data points coincide). a, RT of hip joint moment (M_H) versus RT of smoothed rectified electromyogram (SREMG) of m. gluteus maximus (GLU); b, RT of the vertical component of the ground reaction force (F_z) versus RT of GLU-SREMG; c, RT of ankle joint moment (M_A) versus RT of GLU-SREMG; d, RT of M_A versus RT of SREMG of m. soleus (SOL). Note the one outlier in diagram c. This subject, who had the lowest RT of M_A , kept the plantar flexion moment zero during the major part of the push-off.

correlations between RT of M_H and RT of SREMG of ST and GLU (also see Fig. 6a). However, no correlations were found between RT of M_K and RT of VAS-SREMG or RF-SREMG, nor between RT of M_A and RT of SOL-SREMG or GAS-SREMG. It was concluded from scatter plots such as the one presented in Figure 6d (RT of SOL-SREMG versus RT of M_A) that this was not due to outlying data points. Surprisingly, both RT of M_K and RT of M_A were correlated to GLU-SREMG. As an example, the scatter plot for RT of GLU-SREMG versus RT of M_A is presented in Figure 6c.

DISCUSSION

The purpose of this study was to gain insight into the importance of stimulation dynamics for force development in human maximum height jumping. To quantitate the dynamics of signals, RT were calculated. In the group of subjects participating in this study, a large variation occurred in RT of F_z , joint moments and SREMG of muscles, and correlations were found between RT of several variables, with those between RT of GLU-SREMG and RT of joint moments and RT of F_z being the most intriguing. We

shall first evaluate the observed RT values, subsequently try to explain the aforementioned correlations, and finally speculate on the origin and possible relevance of stimulation dynamics.

Evaluation of observed RT. The first observation to be made is that the RT of SREMG signals are not negligible compared with the duration of the push-off, which was 329 ms on average. The shortest RT, which were found in GAS and GLU, amounted to more than 100 ms on average. The relatively slow RT were no artifact caused by choosing a 10-Hz low-pass cutoff frequency: it was confirmed that they did not change when this cutoff frequency was raised. The average RT of joint moments, 90 ms, 109 ms, and 112 ms for M_H , M_K , and M_A , respectively, were about the same as the RT of the SREMG signals driving them. Does that mean that the speed of force development in jumping is limited by the time it takes to build up muscle stimulation? In the search for an answer to this question, one possible avenue is to compare the RT of joint moments with force RT measured in electrically elicited contractions, in which muscle stimulation may be increased instantaneously and force RT should be minimal. Surprisingly, the RT of joint moments found in this study were not greater than values for time-to-peak tension measured in electrically elicited twitch contractions of human muscle, which are typically of the order of 100–150 ms (11,25,30,32). This is even more surprising if we realize that during electrically elicited contractions, the values for time-to-peak tension in a twitch are smaller than force RT in tetanic contractions, as may be deduced from a few force-time tracings, which we have found scattered through literature (2,3). Thus, if anything needs to be explained here, it is why the RT of mechanical variables in jumping are shorter instead of longer than those in electrically elicited contractions. The explanation may be that the contractions in this study were not isometric; the leveling off and subsequent decrease of joint moments is partly caused by an increase in the shortening velocity. In any case, comparison of force RT in jumping with those in electrically elicited contractions is unsuitable to provide an answer to the question whether the speed of force development in jumping is limited by the time it takes to build up muscle stimulation. Another possible avenue to find an answer to this question is to look at correlations between stimulation and force dynamics. This will be done below.

Correlations between stimulation and force dynamics. One of the strongest correlations found in this study was that between RT of GLU-SREMG and RT of F_z . To explain this surprisingly high correlation ($r = 0.88$), we need to elaborate on how subjects jump and why they jump

that way. Our analysis essentially builds on the mechanics of vertical jumping, particularly on the effects of changes in joint moments on the acceleration of CM. These effects can easily be predicted if we realize that, quasi-statically, the ratio of hip, knee, and ankle moments determines the location of the center of pressure and the direction of the ground reaction force vector (16), with the latter reflecting the direction of the acceleration of CM caused by the joint moments. Let us consider, for instance, the starting position (e.g., Fig. 2). It was found that in this position, most of the subjects have their CM somewhere midway between the ball of the foot and the ankle. Because there is equilibrium, the center of mass lies exactly above the center of pressure, and joint moments are adjusted in such a manner that the acceleration of CM is zero, which means that the ground reaction force is equal in magnitude to the force of gravity and points vertically upward from the center of pressure to the center of mass. If a subject in this position were to activate the knee extensor muscles, an upward-*backward* acceleration of the center of mass would occur. After all, if the knee joint moment is increased without changing the other joint moments, the ground reaction force vector will increase in magnitude and rotate backwards away from the knee joint to the hip joint, reflecting an upward-*backward* acceleration of CM. A similar argument holds for activating the plantar flexors. Activation of these muscles will cause a forward displacement of the center of pressure and a backward rotation and increase in magnitude of the ground reaction force vector, again reflecting upward-*backward* acceleration of CM. An increase of the hip joint moment (relative to the knee joint moment), however, will cause an upward-*forward* acceleration of the center of mass. Thus, an upward acceleration of CM can be achieved by increasing any of the joint moments, but a forward acceleration only by increasing the hip joint moment relative to the other joint moments. This remains true during the push-off, even though the dynamics of the movement slightly disturbs the relationship between joint moments and the acceleration of CM.

Let us now turn to what subjects did in a kinematic sense. During the push-off, they first achieved an upward-forward velocity and displacement of CM, to end with an almost perfectly vertical velocity at toe-off. This requires delicate control of the horizontal acceleration of CM. As explained above, a forward acceleration of CM can only be generated by increasing M_H relative to the other joint moments. The subjects achieved the initial forward acceleration, and the resulting forward velocity and displacement, by increasing M_H earlier and faster than the other joint moments: both $t_{0.1E}$ and $t_{0.9E}$ were reached earlier in M_H than in M_K and M_A ($P < 0.05$). For this purpose, they preferentially used the hamstrings: SREMG of ST and BF reached $t_{0.1E}$ earlier than SREMG of all other muscles ($P < 0.05$). Similar observations were made earlier for countermovement jumps (6). Note that ST and BF are ideally suited to increase M_H relative to M_K and therewith generate a forward acceleration of CM, because they not only increase the extension moment at the hip joint but at the same time reduce the

extension moment at the knee joint. Note also that F_y responds promptly to the activation of the hamstrings: it reaches $t_{0.1E}$ earlier than F_z and the joint moments (Table 1, $P < 0.05$). F_z responds later (Table 1) because it is more sensitive to activation of GLU, which kicks in later than ST and BF; GLU also contributes to the hip extension joint moment but does not simultaneously reduce the extension moment at the knee. After the initial forward acceleration of CM, a backward acceleration occurs (see also Fig. 3) that reduces the acquired forward velocity. The underlying mechanism is obvious: SREMG of ST, BF, and GLU, and correspondingly M_H (and F_y), reach their $t_{0.9E}$ earlier than all other variables ($P < 0.05$) and shortly thereafter start to decrease. M_K and M_A , however, continue to increase and dominate M_H during the last part of the push-off.

The reader may wonder at this point why forward motion of CM during the push-off is so important. We speculate that the associated angular displacements of the body segments benefit the transfer of knee extension and plantar flexion to vertical motion of CM (6,16). If the push-off were initiated by activation of knee and/or ankle extensors, an overall backward rotation of the body would occur with an adverse effect on the transfer of joint extensions on vertical motion of CM, resulting in submaximal jump height. In this context, it should perhaps be pointed out that in countermovement jumps, subjects can initiate the forward motion by reducing the extension moments at knee and ankle joints (and if the arms are not restricted they may also be used for this purpose). According to the instructions given to the subjects to perform a squat jump, this is not an option. However, on closer examination, it turned out that a few subjects had been unable to fully suppress their inclination to reduce M_K and M_A (e.g., the subject whose M_K and F_z histories are shown in Fig. 1).

Armed with the mechanical framework presented above, we can now try to explain the correlations between RT of GLU-SREMG and RT of mechanical variables. We have argued above that although ST, BF, and GLU all contribute to M_H , GLU is most suitable to generate a vertical acceleration of the center of mass. GLU by itself, however, only acts directly on the trunk and upper leg. Thus, activation of GLU will only effectively increase the vertical acceleration of CM if the support base is more or less stable. To prevent the knee from being accelerated downward, it is essential that M_K and especially M_A are increased. This is exactly what happens: M_K and M_A reach their $t_{0.1E}$ value shortly after M_H . To maximize the vertical acceleration of the center of mass, the subjects would perhaps like to maximize all three joint moments, but, as explained above, M_K and M_A need to be accommodated to M_H in such a way that the forward component of the acceleration of the center of mass is preserved. Thus, if M_H increases slowly, so must M_K and M_A , and so will F_z as a result. The relationship between RT of M_H and RT of M_K may be partly obscured by the action of the hamstrings, as explained above, but in a general sense, M_K and M_A are "slaves" to M_H and the muscles driving M_H , particularly GLU. In our view, this explains the

correlations between RT of GLU-SREMG and RT values of the joint moments and F_z (Table 2).

At this point it seems justified to ask why the RT values of M_K and M_A are not correlated to RT values of the SREMG signals of the muscles driving them (e.g., Fig. 6d). For M_K this is perhaps not so surprising, because the extensor moments of the vasti are counteracted by the flexor moments of hamstrings and gastrocnemius, which are simultaneously active. A correlation between RT values of M_A and RT values of the SREMG signals of the plantar flexors, however, was expected. After reexamining the signals, we have the impression that the lack of correlation is due the fact that the time courses of SREMG signals of knee extensors and plantar flexors were not as systematic across subjects as those of the hip extensor muscles. For instance, whereas GLU-SREMG displayed a clear first burst in all subjects, VAS-SREMG kept on increasing during the entire push-off in a few subjects, even during the last part of the push-off when M_K was already decreasing. Also, in some subjects, M_K and M_A and the SREMG signals of muscles driving them increased insidiously, so that $t_{0.1E}$ and therefore RT were not so well defined. This may come as a disappointment, but the major conclusion remains that in spite of the aforementioned limitations and the tangled relationship between EMG and net joint moments, meaningful correlations were found between RT of GLU-SREMG and RT values of mechanical variables.

Origin and possible relevance of stimulation dynamics. In this study, we have shown that the variation in force dynamics across subjects is explained to a large extent by variation in stimulation dynamics of GLU. Obviously, this does not mean that excitation and contraction dynamics do not affect force dynamics in vertical jumping. It merely indicates that variation in stimulation dynamics among subjects significantly contributes to the variation in force dynamics. The coefficient of variation in RT of mechanical variables found in this study was of the order of 30%, which is indeed larger than the coefficient of variation

in variables such as time-to-peak tension measured during electrically elicited twitches of human muscle, which is typically of the order of 6–15% (11,25,30,33). The coefficients of variation in RT of SREMG signals were even greater, reaching values of more than 60%. This brings us to the question why stimulation dynamics varies so much across subjects in the first place. It is hard to believe that this large variation is due to physiologic processes such as the development of excitation in motor unit pools. Therefore, we need to consider the possibility that the central commands to the motor unit pools have a different time course in different subjects. This implies that some subjects are building up these central commands slower than others, perhaps even slower than they possibly could. At first glance, a slowing down of stimulation dynamics will only have undesirable effects on performance. It will cause an increase in the duration of the push-off and, for reasons mentioned in the introduction, a decrease in jump height. Thus, the following question may be raised: Is there, beside these undesirable effects, also a positive effect of slowing down stimulation dynamics? In the search for an answer to this question, it may be relevant to note that in a forward simulation study using instantaneous (“bang-bang”) changes in stimulation, jump height was found to be highly sensitive to small variations in timing of muscle stimulation (7). Perhaps a slowing down of stimulation dynamics serves to reduce the sensitivity of jump height to “errors” in the timing of muscle stimulation. This speculation will be investigated in a future simulation study. In any case, the results of the present study imply that the use of “bang-bang” control (i.e., instantaneous changes in stimulation) in simulation models of vertical jumping (20,22,28,37) may lead to unrealistically fast force development.

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